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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

AIRCRAFT
ENGINE
OILS

PUBLISHED BY
THE TEXAS COMPANY
TEXACO PETROLEUM PRODUCTS

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FOR THE AVIATION INDUSTRY

LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

Published by

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AIRCRAFT ENGINE OILS

BEFORE entering into an all-out discussion of lubricants for aircraft engines, it might be well to consider something of the nature of the present-day piston-type aircraft engine and how it got that way. Every reader is familiar with the fact that the engines used to power military, commercial, executive and personal aircraft of today are indeed a far-cry from the small power plant which urged the Wright machine into the air at Kitty Hawk, or even the engines which powered the military aircraft of World War I. From a multiplicity of engine types—liquid-cooled, air-cooled, in-line, vee, inverted, opposed, rotary, radial, H-, barrel and many others—which existed twenty and more years ago, the types of engines currently in manufacture and wide usage have narrowed down to principally these three:

1. Air-cooled radial engines; including the smaller direct-drive or geared unsupercharged engines used in trainers and private aircraft, with ratings up to 350 hp.; the intermediate types, supercharged, delivering from 450 to 800 hp.; and the larger, highly supercharged engines for military and commercial use, ranging from 1200 to 3500 hp. for take-off. Such engines power the largest long-range bombers as well as the post-war U. S. transports which have set the standards for world-wide airline operation.

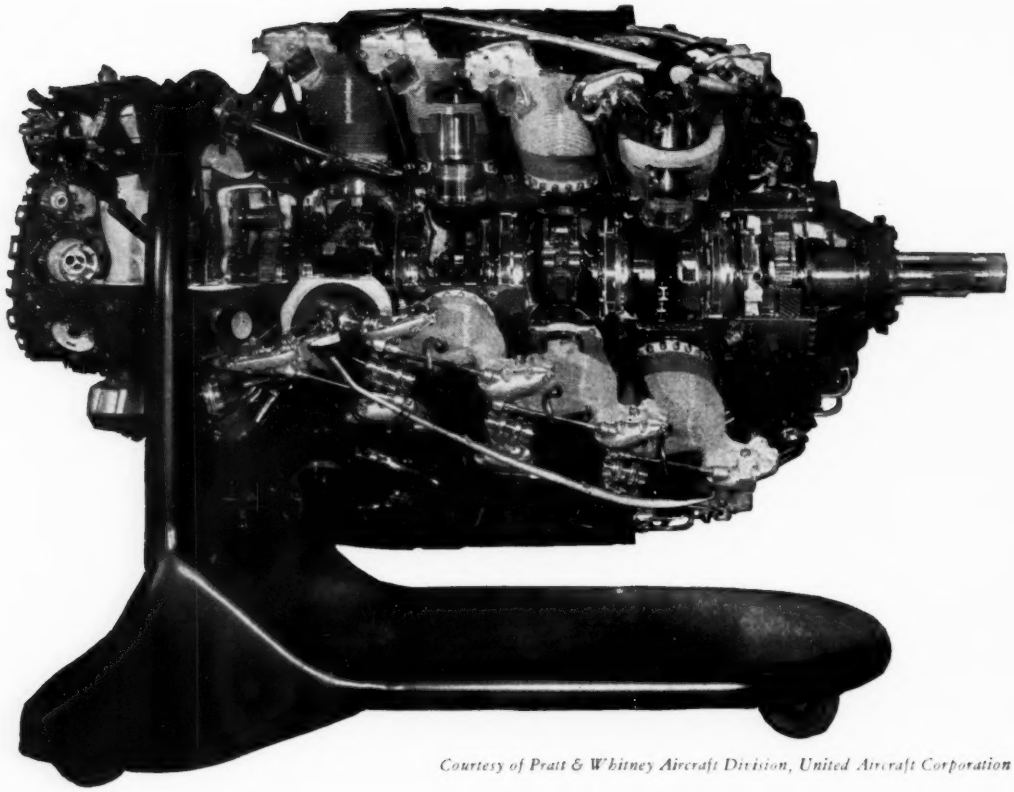
REGARDLESS of the increasing importance of mechanical and electrical components to operation of aircraft, the aircraft engine is still the most important single factor in flight operations, for upon the engine depends the power for flight. Just as the airplane depends upon its engine or engines for power, so does the engine rely upon fuels and lubricants for the ability to sustain this power. The remarkable advances in aviation accomplished within the last two decades, in fact within only the last decade, have been built upon the mutual reliability and dependability of engines and the petroleum products which they use. Previous issues of Lubrication have covered the fuel and lubricant requirements of the newer gas turbine and jet power plants and a description of oil systems of reciprocating aircraft engines. The present article deals with the lubricant requirements of the modern reciprocating aircraft engine.

2. Air-cooled, horizontally-opposed engines for private and executive aircraft, trainers, military liaison planes and smaller commercial craft, having either four or six cylinders and take-off ratings from 65 to 260 hp.

3. Liquid-cooled, V-type engines for military and air transport use, the most popular types having twelve cylinders and developing maximum powers up to 2500 hp. Engines of this type powered the famous "Spitfire", P-51 "Mustang", and P-38 "Lightning" fighters of World War II and are used in transport aircraft by foreign operators.

LUBRICATION SYSTEMS

Details of internal oil systems within the engine and external oil systems which are a part of the aircraft power plant installation were described in the May 1951 issue of LUBRICATION. Emphasis



Courtesy of Pratt & Whitney Aircraft Division, United Aircraft Corporation

Figure 1 — Cut-away model of a Pratt and Whitney Model R-4360 Wasp Major aircraft engine.

was also given to the inter-relationships of oil system design and satisfactory operation of the oil system in service. External oil system details were shown to be particularly important in relation to service problems such as provisions for starting at low temperatures, accumulation of contaminants in the oil system, and operation at high altitudes.

In order to provide a background for consideration of lubricants, some of the features of the internal oil system will be reviewed briefly. The interested reader is referred to the previous article for more detailed information, however.

It is of particular interest to note that in all of the types of engines listed above, except the smaller sizes of horizontally-opposed engines, a dry sump system is used. In the conventional dry sump system, the oil supply is carried in an external tank and oil is delivered to the engine directly from the tank. One or more main oil pumps supply oil under pressure to different parts of the engine through various routes and passages. Return oil is picked up by scavenge pumps which return it to the tank through an external system including an oil cooler. Chief advantages of the dry sump system have been listed as flexibility in size and location of oil supply tank, better control of oil temperature, and ability to operate at any airplane attitude and altitude with proper design.

The wet sump system differs from the dry sump system in that the oil supply is carried in the engine oil sump or crankcase much as in automotive engines. As in the dry sump system, a pressure pump supplies oil to the internal lubrication system and return oil drains back into the crankcase sump. Advantages of the wet sump system are simplicity and low cost and this system is entirely adequate for the smaller engines in which it is used. Oil temperatures may run higher in the wet sump system, however, due to the lack of direct cooling of the return oil, and higher temperatures may in turn affect the service life of the lubricant.[1]

LUBRICANT REQUIREMENTS

The selection of lubricants for aircraft engines must necessarily be tempered by consideration of engine requirements and the environment in which the oil is to be used. The modern aircraft engine and the type of lubricant which it likes best have resulted from a mutual development throughout many years. Thus engines and oils are inter-depend-

[1] LUBRICATION, May 1951, "Aircraft Engine Oil Systems"

able, and present-day aircraft engine oil requirements represent an engineering compromise to the problems imposed by the engine and its service environment. The properties of oil found most suitable have been evolved from experience in making alternate compromises throughout the mutual development of engines and oils. For instance, during the development of a new engine a particular piston and ring configuration may have been found to suffer from rapid and severe ring sticking with available oils that previously gave satisfactory performance. Modification of the piston and ring design may be undertaken to relieve the problems; by the same token, oils with improved stability and resistance to ring sticking may be developed to aid the solution. In such a manner engines are designed to operate satisfactorily on the oils which they will use, and oils are developed to meet the needs of the engines in service. A listing of the physical properties of the present-day high-quality aircraft engine oils may be prefaced by a look at the service and environmental elements of the engine.

Service Environment

The two outstanding properties of the conditions to which oil is subjected in an aircraft engine are (1) temperature, and (2) contamination. The importance of temperature results not only from the high temperatures prevailing within an air-cooled aircraft engine and the low temperatures attending high-altitude operation, but also from use of the oil as an internal engine coolant. Use of the oil as an internal coolant has been employed since many of the earliest engines; however, the heat load placed upon the oil has been increased tremendously, beginning with the high-powered radial air-cooled engines that were introduced in the 1930's and continuing into the larger models of today. The amount of heat rejected to the oil is reflected by an oil temperature rise of 60 to 70°F. between oil in and oil out temperatures of modern engines, despite oil circulation rates as high as 50 gallons per minute (Table I). A number of years ago it was reported that the proportion of total heat rejection in an engine (cooling load) carried by the oil amounted to 11 to 25% in then-current designs, and the heat rejection to oil is known to be even higher in some of today's models. With oil-out temperatures as high as 240°F., it is apparent that maximum oil temperatures within the engine are many degrees higher. In fact, at one of the most severe locations in the oil system temperature-wise, the exhaust rocker box, the oil is subjected to temperatures of 600°F. and greater.

On the other extreme, bulk oil temperatures outside the hopper in the oil tanks of some high altitude aircraft may approach operating altitude temperatures, although 75 to 100° F. is a more general minimum due to some heating of the tank oil from warm oil in the hopper.

Oil system temperatures lower than 130-140° F. accentuate one of the most serious problems with respect to contamination of the oil, namely condensation of water.[2] The inevitable presence of water as a result of condensation of exhaust gases in the engine and oil systems makes the demulsibility and water separation characteristics of the lubricant vitally important. Low temperatures retard or prevent release of the water as vapor, making the load upon the oil that much more severe.

Additional sources of contamination, other than abrasive particles from engine wear, are found in the products of incomplete combustion from the fuel which enter the oil through exhaust gases which impinge on the oil or oil film in the cylinder wall-piston ring areas or at the exhaust valve guides. These blow-by contaminants are principally of two types: first, incompletely oxidized hydrocarbons from the fuel, occurring mainly at rich-mixture operation such as take-off and climb, and second, the decomposition products of tetraethyl lead, used to increase the anti-knock value of the fuel. The lead products finding their way into

[2] LUBRICATION, May 1951, "Aircraft Engine Oil Systems"

TABLE I

Oil Flow Data of Some Current Engine Models

Engine Displacement, Cu. In.	*1300*	*1820*	*1830*	*2000*	*2800*	*3350*	*4360*
Normal Take-Off Rating, HP[1]	800	1475	1200	1450	2100	2500	3250
RPM	2600	2800	2725	2700	2800	2800	2700
Normal Rated Power, HP	700	1275	1050	1200	1800	2100	2800
RPM	2400	2500	2550	2550	2600	2400	2550
Maximum Oil Flow[2] at Rated RPM, Approx. Gals. per min., at Oil-In Temp.	14	18	14	19	29	36	50

[1] Without water injection

[2] In round numbers, actual service limits are given in lb./min. at flight conditions

TABLE II

Identification of Lead Compounds found in Aircraft Engine Combustion Chambers

Location	*Major Component*	
Exhaust Valve Dome	4 PbO. Pb SO_4	(4 Parts Lead Oxide—1 Part Lead Sulfate)
Exhaust Valve Tulip	PbO. Pb SO_4	(Approx. Equal Parts of Lead Oxide and Lead Sulfate)
Intake Valve Dome	PbO. Pb Br_2 2 PbO. Pb Br_2	(Lead Oxide and Lead Bromide)
Piston Crown	PbO. Pb Br_2 2 PbO. Pb Br_2	(Lead Oxide and Lead Bromide)
Combustion Chamber Walls		
Nodular Deposits	PbO. Pb SO_4	(Lead Oxide and Lead Sulfate)
Fused Deposits	2 PbO. Pb Br_2	(Lead Oxide and Lead Bromide)

Engines operated on Grade 100/130 aviation gasoline containing 3.0 to 4.0 ml/gal T.E.L., aviation mix.

aircraft engine oil are made up of a great many compounds but are chiefly lead oxide, lead bromide, combinations of oxy-bromides, lead sulfate, and metallic lead. Theoretically, the aviation tetra-ethyl lead mix in the fuel is compounded with sufficient ethylene dibromide to provide conversion of the lead to lead bromide; however in various engines and at different conditions of operation, the completeness of conversion varies and a range of lead compounds is formed, Table II. The engine oil must satisfactorily disperse and carry the finely divided lead compounds which enter the oil system and must resist the deteriorating effects of these materials, as well as the incompletely burned fuel hydrocarbons that often have binding or resin-forming properties.

Perhaps a comment is in order to clarify that present aviation gasolines are developed and selected to have optimum volatility and burning properties, as well as stability, in order to reduce to an absolute minimum the formation of incomplete products of combustion. Nevertheless such products are the inevitable result of rich mixtures as required for high power operation of aircraft engines. Likewise, the performance and economic advantages of tetra-ethyl lead for increasing fuel knock ratings far out-weigh its disadvantages, hence lead residues in the oil cannot be eliminated by dispensing with the use of leaded fuels. It also can be mentioned that extensive research has been and is being conducted toward the development of improved lead scavenging agents to convert the tetra-ethyl lead to materials other than lead and lead oxides and remove it more completely in the exhaust gases.

Physical Requirements

The service environment, then, is seen to affect

TABLE III

Aircraft Engine Lubricating Oil Specifications

Specification	*Grade Designation*			
MIL-0-6082	*65*	*80*	*100*	*120*
Requirement	*(1065)*	*(1080)*	*(1100)*	*(1120)*
Flash Point, °F, Min.	420	450	470	490
Pour Point, °F, Max.	0	0	+10	+20
Diluted Pour, °F, Max.	—	—65°F.	—65°F.	—
Viscosity, SUS, @ 210°F.	62-68	76-84	93-103	115-125
Viscosity Index, Min.	100	100	95	95
Carbon Residue %, Max.	0.6	0.9	1.2	1.5
Sulfur, Wt. %, Max.		0.5		
Corrosion, Copper Strip at 212°F.		No black or brown discoloration or pitting		
Precipitation No.		Zero		
Saponification No., Max.		0.5		
Neutralization No., Max.		0.10		
Ash, %, Max.		0.0025		

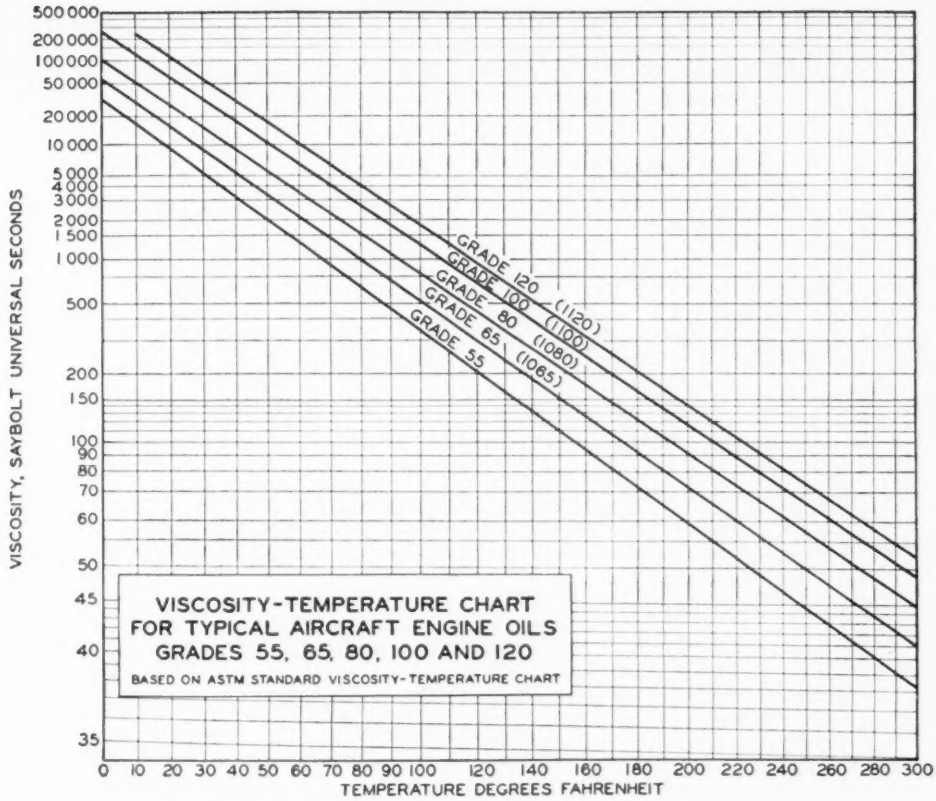


Figure 2 — Viscosity-temperature chart for typical aircraft engine oils.

the lubricant requirements for aircraft engines, along with bearing and gear design, loads, speeds, and other features of the engine itself.

To meet these conditions there has been developed a series of petroleum-base straight mineral lubricants, classified according to viscosity grades, to cover the requirements of all types of engines. Physical characteristics and inspection tests on such a series of lubricants are shown in Table III. Inspection tests of currently used oils generally will meet the minimum requirements of government specification MIL-0-6082, describing oils for military aircraft reciprocating engines. This specification is the evolutionary descendant of Specs. USA-2-91, 2-91-A, AN-VV-0-446, and AN-0-8, which will be familiar to many readers. While it is a correct premise of the military specification that the product it describes must be operable in aircraft engines, the specification consists only of physical and inspection tests as noted above and there is nothing to insure that optimum performance will be obtained from oils merely meeting the minimum specification requirements. Later sections will discuss additional means taken by leading refiners to assure that oil performance, as well as specifications, will be "on test".

A brief run-down on the more important requirements, how they are determined, and their significance is given hereafter:

Viscosity

The basic purpose of lubrication is to reduce friction and wear through providing an oil film or layer between moving parts. The most important single lubricant property in determining the characteristics of this film is the viscosity, commonly called the "body" or "weight" of the oil. Viscosity is also a measure of the fluidity or resistance to flow of the oil and for this reason, viscosity is normally measured in terms of the time required for a given amount of oil to flow through an orifice at specified temperatures.

The accepted procedure for determining aircraft engine oil viscosity is conducted with the Saybolt Universal Viscosimeter, in which 60 ml. of oil are timed through a standard orifice and results are expressed as Saybolt Universal Seconds or SUS. Standard temperatures are 210° and 100°F., with viscosity grades based upon the viscosity at 210°F. It is convenient to remember that the commonly used aircraft engine oil grade designations — 55, 65, 80, 100 and 120 are approximately the vis-

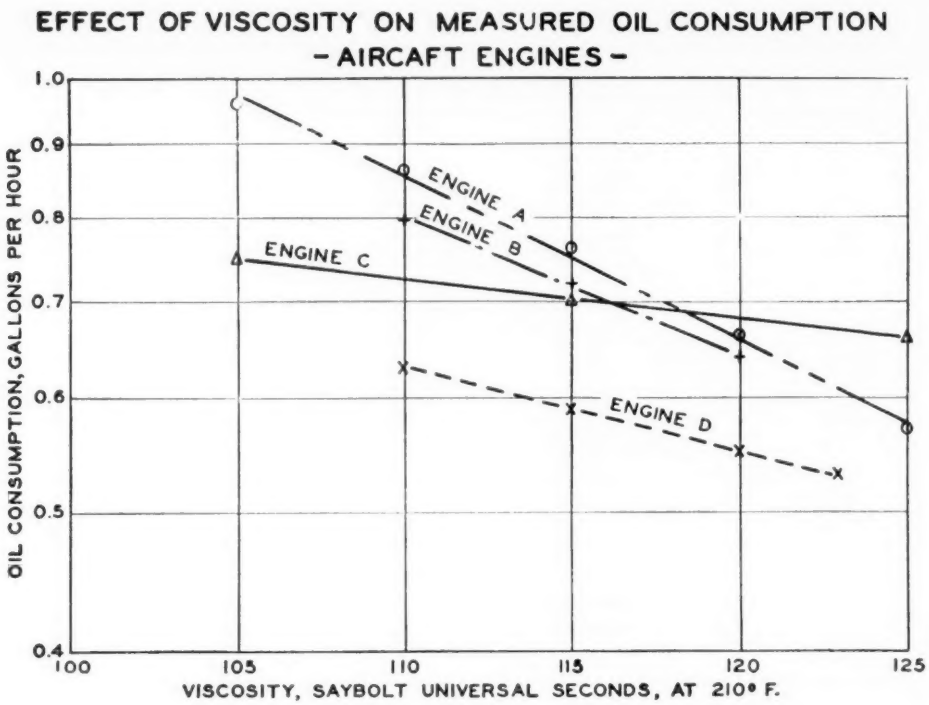


Figure 3 — Effect of oil viscosity on measured oil consumption.

cosities, SUS, at 210°F. for these grades, allowing for specification tolerance. Thus grade 120 aircraft engine oil has a Saybolt viscosity of 115 to 125 seconds at 210°F. Saybolt viscosity may be readily converted to Kinematic viscosity, which is the physical property related to oil flow and film thickness by mechanical analysis. Many laboratories prefer to determine Kinematic viscosity through determination in Fenske or modified Ostwald-type viscosimeters.[3]

Viscosity is significant in aircraft engines through determining oil flow rates, friction, and oil film thicknesses in fluid film lubricated bearings. The relation of oil consumption to viscosity, as influenced by oil flow rates, in one engine model in commercial transport service is shown in Figure 3. Given engine models also are designed to operate best on a definite oil viscosity, and pump and passage sizes, as well as bearing and gear design, are selected with this in mind. For this reason it is well to follow the recommendations of the engine manufacturer as to viscosity grade and seasonal changes. In certain specific cases the recommendation of the manufacturer may be tempered by operational experience with given engines, and considerations such as type of service, or unusual wear or consumption rates, may dictate the use of a higher or lower viscosity, to which the manufacturer's approval should always be obtained.

Effect of Temperature on Viscosity — Viscosity Index

It is well known that the viscosity of oils changes rapidly with temperature, oils becoming thicker or more viscous as temperatures are lowered and thinner or less viscous at elevated temperatures. Because oils are used at temperatures much lower than the specified 210°F. of the Saybolt determination for starting and also in portions of the oil system in use, and at temperatures higher than 210°F. in hotter parts of the engine, it is desirable to control the change of viscosity with temperature to certain practical or acceptable levels.

A standard concept for expressing the change of viscosity with temperature is Viscosity Index, abbreviated V. I. In developing the V. I. scale, a certain naphthenic oil which changes viscosity with temperature rapidly was given a value of Zero V. I., and a corresponding highly paraffin oil was arbitrarily assigned a V. I. of 100. The Viscosity Index of other oils is determined according to the relative change in their viscosities at 100° and 210°F., in comparison with the viscosities of these arbitrary standards.[4]

[3] See LUBRICATION, May 1950, "Viscosity — Part I", and June 1950, "Viscosity — Part II", for a more complete discussion of viscosity and its measurement.

[4] LUBRICATION, April 1945, "Viscosity and Viscosity Index"

The minimum Viscosity Index of present grade 100 and 120 aircraft engine oils is approximately 95 V. I. Table IV illustrates the significance of V. I. in controlling change of viscosity with temperature. It will be noted that for equal viscosities at 210°F., the oils of higher V. I. have lower viscosities at 100°F. and 32°F., aiding in easier starting and more rapid build-up of oil flow when cold. At 300°F., the viscosities of the higher V. I. oils show less drop, providing a greater operating viscosity at engine locations with higher temperatures. For purposes of comparison, an oil of Zero V. I. is also included, although other properties would make an oil of this type unsuitable for modern aircraft engines.

Beyond establishing a given rate of change of viscosity with temperature, Viscosity Index has no great significance in aircraft engine oils and is not a criterion of quality. It is true that a V. I. in the range of 95 serves to limit acceptable oils to highly paraffinic, or solvent-refined mixed-base oils, which have desirable properties in high temperature stability and film strength, however these and similar properties do not correlate with small variations in V. I. above the 85 or 90 V. I. level. Thus aside from a few seconds difference in viscosity at lower or higher temperatures, there is not necessarily any significant difference between aircraft engine oils of 95 V. I. and, say, 100 V. I.

Pour Test

The pour point of an oil is defined as the lowest temperature at which the oil will pour or flow under prescribed conditions. The pour point in degrees Fahrenheit is determined to the nearest five degrees by chilling the oil sample slowly in standard apparatus and inspecting for flow at 5°F. intervals.

The pour test is not an absolute indication of pumpability or lowest usable temperature for an oil although it does have some value in describing relative low temperature properties. Thus oils often may be pumped at temperatures below their pour points and, conversely, factors other than pour may render the oil inoperative for certain purposes at temperatures above the pour point. As regards cold starting with grade 100 and 120 aircraft engine oils, for instance, the initial high viscosities and the increase in viscosity as temperatures are lowered results in viscous drag becoming a limitation to starting well above the normal pour points of 0°F. and +10°F. for grades 100 and 120, respectively.

Tests with several different models of larger aircraft engines have shown that cranking torque becomes excessive and cranking speeds too low to insure reliable starts when lubricating oil viscosity reaches the neighborhood of 30-50,000 SUS. A working maximum of 35,000 seconds is used by some designers.[5] Grade 100 and 120 oils reach this viscosity at about +25°F. and +32°F., respectively. Thus viscosity limits starting above the pour point although the oils are still pumpable and will flow.

Diluted Pour

The limitation to cold starting due to increased viscosity has led to the practice of diluting engine oil with gasoline whenever low temperatures are expected and facilities are not available for heating the engines prior to starting.[6] This makes it necessary for some control to be placed on the pour point obtained when the oil is diluted with a given quantity of aviation gasoline or equivalent diluent. Military Specification MIL-0-6082 requires that 80 and 100 grade oils have a pour point no greater than —65°F. when diluted with 30% of a standard diluent.

Other Physical Tests

Certain other physical tests are included in aircraft engine oil specifications chiefly as a result of historical precedence, although some of the tests

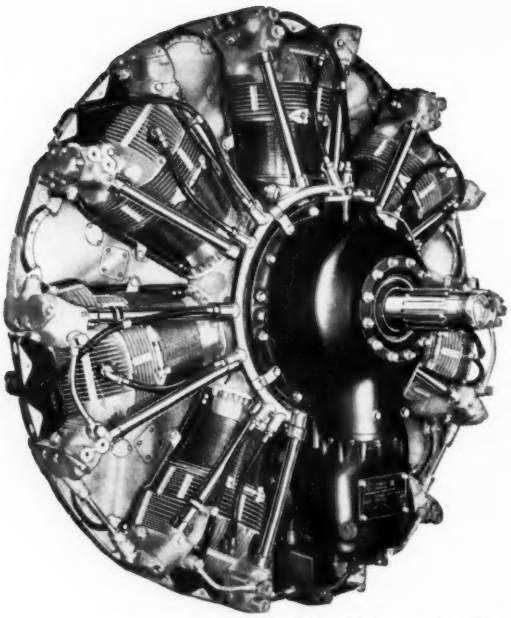
[5] LUBRICATION, May 1951, "Aircraft Engine Oil Systems"
[6] See Ref. 5 for a more complete discussion of dilution practices.

TABLE IV

Effect of Viscosity Index on Viscosities at High and Low Temperatures for Oils of Same Viscosity at 210°F.

Viscosity Index of Oil	*Viscosity, Saybolt Universal Seconds at Stated Temperature*			
	*32°F**	*100°F†*	*210°F*	*300°F**
0	Over 300,000	3838	120	47.5
80	Approx. 70,000	2064	120	50.9
90	Approx. 50,000	1842	120	51.8
100	Approx. 35,000	1620	120	52.7

*Extroplated Viscosities
†From ASTM Viscosity Index Tables



Courtesy of Wright Aeronautical Corp.

Figure 4 — ¾ Right side view of the Wright cyclone 7. The 800 H.P. Cyclone 7 powers the USAF T-28 trainer.

have limited value in defining the type of product desired or for manufacturing control by the supplier. These tests are covered briefly as follows:

Flash and Fire Tests

The flash point of an oil is the temperature to which the oil must be heated in order to give off sufficient vapor to form an inflammable mixture with air under the conditions of the test. The fire point is the temperature to which an oil must be heated to burn continuously after the air-vapor mixture is once ignited. Flash and fire temperatures should not be confused with spontaneous or autogenous ignition temperatures, since an ignition source such as a test flame is used to ignite the air-vapor mixture in flash and fire tests.

These tests have general significance in indicating the fire hazard of petroleum products. They are also useful in indicating dilution with gasoline or light products for used oil tests since the presence of even small amounts of diluent depresses the flash and fire points markedly. Aside from this, flash and fire points are principally useful in product control by the refiner, although some purchase specifications still list minimum values.

Color

Allowable color standards are a feature of nearly all specifications, although there is certainly no direct connection between slight color variations and quality. In a broad sense, a color limitation may be used to indicate a desired degree of refining or freedom from impurities in the oil. Color is determined by matching in a standard colorimeter such as the ASTM or Saybolt apparatus. Its principal usefulness, again, is for manufacturing control by an individual refiner where much closer control may be obtained than is possible for a range of oils produced by several different refiners from various crude sources.

Carbon Residue

There have been attempts to relate the residue remaining after destructive distillation of an oil, to the engine deposit forming tendencies of the oil, with but little success unless very high variations in carbon residue are considered. The standard test, ASTM Method D 189, Conradson Carbon Residue, involves the destructive distillation of a given quantity of oil in a standardized apparatus with all air excluded. Carbon residue is reported as per cent of the original sample remaining as residue. Very unstable oils or those with high carbon forming tendencies will be excluded by specification limits on carbon residue, hence the test has some value. Due to the absence of oxygen in the test, however, carbon residue values give no indication of the oxidation stability of oils.

Ash

Ash is determined by burning a small amount of oil completely and weighing the remaining ash. Values are reported in per cent of original sample. Ash values on unused aircraft engine oils are very low, ranging from none to perhaps 0.001%. For this reason the test has little significance except to indicate freedom from impurities. On used straight mineral oils, the ash value increases as a result of lead compounds and foreign particles carried in the oil and may be used as a rough indication of the amount of contaminants of this type.

Neutralization Number

Like ash, Neutralization Number is very low on properly refined unused straight mineral oils, where its principal use to the refiner and user is to indicate freedom of acids from treating processes during manufacture. Neutralization Number is defined as the number of milligrams of potassium hydroxide required to neutralize one gram of oil. On purely oxidized straight mineral oils containing no foreign contaminants Neutralization Number is an indication of organic acidity, however on used aircraft engine oils the lead compounds and residues that are always present react with the potassium hydroxide to give a Neutralization Number that is not indicative of acidity from oil oxidation. Care therefore must be taken in interpretation of values obtained on used oils.

Oxidation and Corrosion Resistance — High Temperature Stability

Oil specifications normally require only that the oil shall be non-corrosive to a freshly polished copper strip when submerged for three hours at 212°F. In view of the use of lead plated bearings in main and master rod locations as well as others in many engines, progressive refiners add a lead strip corrosion test to their own inspection tests.

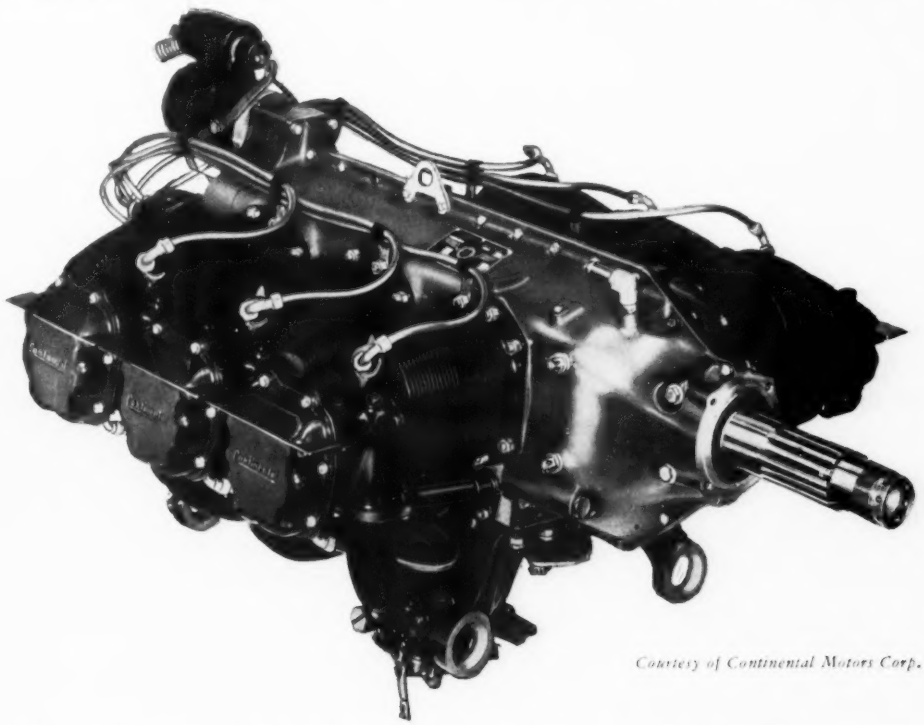
In addition, special oxidation and corrosion tests are used by leading refiners to check these properties and as a basis for oil improvements. Among such tests is the MacCoull Oxidation and Bearing Corrosion Test, developed jointly with Pratt and Whitney Aircraft.[7] In this test small test bearings are inserted on rotating spindles in a beaker of heated oil, rotation of the spindle circulates oil through the bearing and sprays the oil through air at the surface to provide oxidizing conditions. Tests are normally made at 250°F. and 350°F. for aircraft engine oils, and, in addition to the standard copper-lead test bearings, lead-flashed bearings similar to aircraft engine bearings are used. Bearing corrosion is determined by bearing weight loss on the test bearings at specified intervals, while used oil tests indicate the degree of oil oxidation. Very good correlation has been obtained between results of this test and engine tests.

Other specially developed tests are employed to indicate deposit and corrosive tendencies of oils, using test conditions and materials selected to provide similitude with actual operating conditions. Such tests as a bench valve guide corrosion test, to check corrosion of bronze exhaust valve guides, and various high temperature deposits tests, to determine deposit forming characteristics under thin-film, very high temperature conditions, are used as an index of oil quality and a guide to future improvements. It is in performance tests such as these, as well as specific engine tests, that oil specifications fall short and the initiative of the individual refiner becomes paramount in establishing true indications of oil quality.

Film Strength — Load Carrying Properties

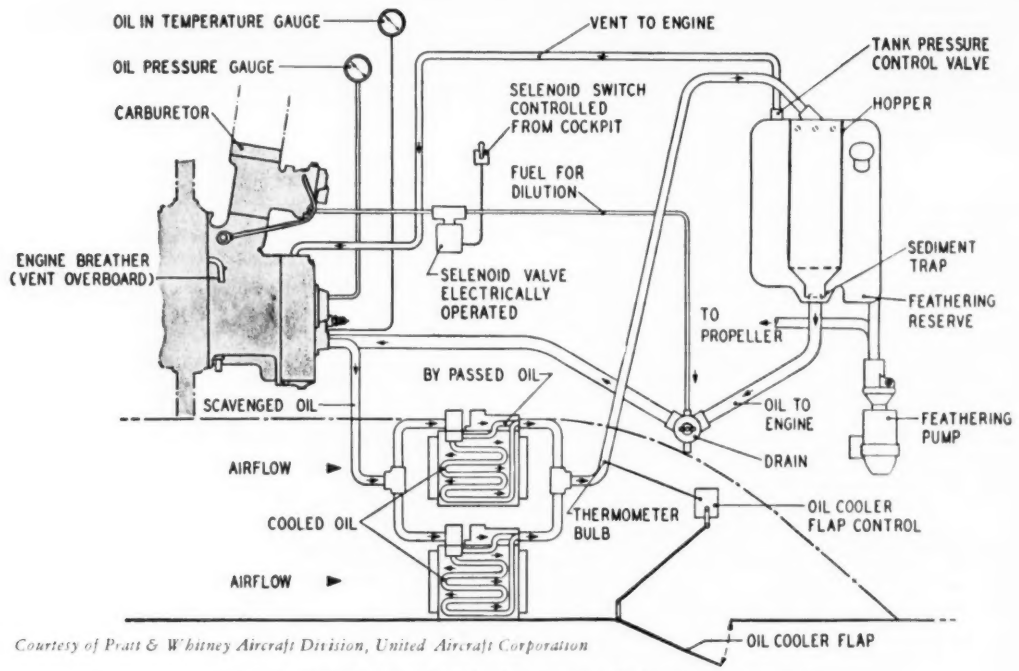
The present type of aircraft engine oil is outstanding among straight-mineral or uncompounded oils in the load carrying properties which are desirable in lubricating propeller reduction gears and accessory drive gears. The necessity for minimum weight and the availability of high strength, precision gears has led to the use of high gear loads. Present aircraft oils owe their excellent gear lubrication properties not only to their heavy body

7 "An Oil Corrosion Tester", N. MacCoull, E. A. Ryder, and A. C. Scholp, SAE Trans., 1942, p. 338.



Courtesy of Continental Motors Corp.

Figure 5 — Horizontal-opposed air-cooled aircraft engine of the type popularly used in private and executive aircraft. Model shown is the 6 cylinder Continental Model E-185.



Courtesy of Pratt & Whitney Aircraft Division, United Aircraft Corporation

Figure 6—Typical external lubrication system with hopper type oil tank.

or viscosity and high V. I. or maintenance of viscosity at high temperatures, but also to the oxidation resistance features of the type of refined products from which they are selected.

Precipitation Number

The precipitation number test on oils is a measure of the material in the oil which is insoluble in "precipitation naphtha", a light naphtha which is standardized by the A.S.T.M. New oils of the type used for aviation lubricants contain none or negligible quantities of material which would be indicated in this test. Precipitation number or similar naphtha insoluble tests are useful in evaluating used oil where contaminants or insoluble products developed in service are present.

Saponification Number

This test determines the acidic and basic constituents produced upon saponification of oils under the test conditions. It indicates the presence of both free and combined fatty acids. A very low saponification number is characteristic of new aircraft engine oils; on used oils the test may serve to indicate the extent of oxidation which has occurred, although the presence of lead and other metals which form soap complexes makes interpretation of the test difficult.

EFFECT OF SERVICE

So far, except for brief references to the effect of used oils on certain inspection tests, attention has been confined to the properties of unused oils. What then is the effect of service use on properties of present straight mineral aircraft engine oils?

As oils are used in an engine in service, several different changes may take place. As a result of exposure to high temperatures and air, the oil may combine with oxygen, or oxidize. Oxidation of oil results in a range of products being formed, some of which are heavy tarry, varnish forming materials. Oxidation products usually darken the oil and may result in large increases in viscosity. On the other hand, as has already been mentioned, the oil also becomes contaminated in service. Contaminants include fuel soot and incompletely burned fuel substances, lead and lead products, wear particles, and water.

Used oil tests from many different kinds of aircraft operation indicate that by far the greatest proportion of aircraft engine oil deterioration in service is due to contamination, rather than oxidation. Thus, large increases in viscosity and neutralization number in service are nearly always directly traceable to contamination of the oil with combustion products. Another indication of contamination is found in the proportion of oil insoluble materials carried in the oil. Insolubles have been found to correlate directly with rise in viscosity and neutralization number, as would be expected if contamination is responsible.

This does not mean that aircraft engine oil will not oxidize at high temperatures, for it will, but

that oxidation is not the primary cause of oil deterioration in most aircraft engine service today. Exceptions are found in some smaller or wet sump engines not provided with oil coolers where oil temperatures are high, although in such service the use of shorter oil drain periods limits the amount of oil oxidation to acceptable levels. Contamination from products of incomplete combustion is also prevalent in such engines but may be secondary with reduced drain periods — 100 hours or less.

Service Problems

Among the service problems affecting aircraft engine oil operation are build up and deposition of lead sludges within the engine, varnish and lacquer formation, including the heavy coke-like deposits found at areas of extremely high temperature, and piston ring sticking.

Lead Sludges

Lead sludges found in aircraft engines are of two principal types (see Table V):

1. Hard, dense, almost dry type sludges which collect at points of high centrifugal or inertia force such as crank-pin cavities. These sludges may run as much as 85% or more lead by weight and the amount of oil or oil products often is less than 10%.
2. Loose, fluid type sludges, gray or black in color, which are found at points of lesser centrifugal action in the oil system and clinging to outside walls of front and rear cases, especially in locations where the oil contacts metal surfaces which are exposed to low outside air or carburetor air temperatures on the other side. These sludges usually are not over 30% lead by weight and, if front or rear case sludges, often contain a small amount of water which acts as an emulsifying agent or binder in holding the sludge together.

Formation of both of these types of sludge is related to engine design and conditions of operation of the engine and oil system. Thus the amount of blow-by and the products contained in blow-by, condition of exhaust valve guides, oil system temperatures, oil flow rates, and centrifuging forces at various points within the engine are factors which influence sludge formation, especially the dense type sludges. Elimination of extremely low temperatures and moisture condensation in the oil system has been most effective in reducing or eliminating fluid sludges.[8] Among the methods of attack that have been or are being employed on the centrifuged sludges are redesign of crank-pin cavities to bleed off or control location of the sludge, use of oils with greater dispersion to hold the lead in suspension in the oil, filtration to remove the sludges before they reach high concentrations in the oil and deposit out, and the use of shorter oil drain periods. The last two of these are considered further in the following paragraphs:

Filtration — Large aircraft engines are not now equipped with oil filters other than oil-in and oil-out screens, although service testing of filters is an active item at the present time. For reasons of size and safety, the filters normally are installed in parallel with oil coolers. Problems such as the necessity for frequent servicing of filters due to

[8] LUBRICATION, May 1951, "Aircraft Engine Oil Systems"

TABLE V
Analysis of Typical Aircraft Engine Sludges

Sample	*Fluid Lead Sludges from Rear and Intermediate Cases*	*Crank-Pin Cavity Lead Sludges*
Appearance	Heavy, lumpy gray liquid	Hard, dense dark gray clay-like solid
Analysis		
Oil, %	54	8
Oxidation Products, %	6	1
Carbon, %	21	6
Free Mineral Matter, %	8	85*
Volatile Matter, %	11	Less than 0.1
Total	100	100
Ash, Total, %	6	75
Lead, %	8	60

*Break-Down of Free Mineral Matter, Basis Total Sludge

Lead Oxides, combined with Lead Bromide, %	40
Lead Oxides, combined with Lead Sulfate, %	8
Free Lead, Pb, %	37
	85

the large amount of material collected or determination of optimum filter size to handle the requirements may be evaluated by the current programs. It is too early to evaluate the results, but whatever the outcome of individual test programs, support must be given to the general principle of filtration for removal of insoluble oil contaminants.

Drain Periods — Increasing the frequency of drain periods, from no drain between engine overhauls down to oil drains at 100 hour intervals, has been evaluated in several different engine types for effect on reduction of lead sludges and improved engine cleanliness. In most cases, results have been negative, in that shortened drain periods did not result in a decrease in the amount of lead sludges, determined by weighing the sludges at engine overhaul, nor in improved over-all cleanliness. Used oil tests conducted in conjunction with some of these tests also failed to show any over-all improvement in oil condition as a result of shortened drain periods.

Here again a precautionary note is advisable, for the engines in question were all operated in air transport service where daily utilization was high, elapsed calendar time between overhauls relatively short, and conditions of operation and maintenance favorable. In military and private operations, such conditions may not prevail, making it advisable to use short drain periods to remove contaminants for reasons of safety and good practice, although the oil itself is not "worn out".

Varnish, Lacquer and Coke Deposits

Thick heavy varnish, flaky or granular lacquers, and heavy coke deposits may form on engine parts and surfaces with high operating temperatures. Although there are differences between oils in this respect, excessive formation of deposits with high-quality oils is a reflection of excessive heat at that location. Deposits not only impair heat transfer from the already over-heated parts but also may come loose and clog oil screens or small-diameter oil passages. Heavy exhaust valve stem deposits may result in valve sticking or excessive guide wear.

A focal point of attention during recent years has been coke formation in exhaust rocker boxes of certain large, high-powered engines. Excessive coke is not found in all cylinders, the coke generally being heaviest in cylinder locations having the highest temperatures and lowest oil flow to rocker boxes. Although oil quality is no doubt a secondary factor in coke formation, the solution to excessive coke is being found in improved valve and guide materials which maintain initial clearances throughout engine overhaul life, increased oil flow, and improved heat transfer in the exhaust rocker box area. Using only the first two of these modifications, quite low and acceptable amounts of deposit are obtained in all cylinders with present high-quality straight mineral oils. Coke appears to form principally when a scanty supply of oil impinges in droplets on rocker box and guide tip surfaces operating at over 600°F. The importance of blow-by up the guide as a result of large increases in stem-to-guide diametral clearances is indicated from analyses of so-called rocker-box coke, Table VI.

Ring Sticking

Piston ring sticking from oil deposits is not currently a problem in large radial aircraft engines employing wedge-section rings and high oil flows which aid in cooling the pistons. Ring sticking is sometimes encountered in other engines, however, especially certain of the four-cylinder opposed models and smaller radial engines. In many cases ring sticking may be traced to excessive cylinder barrel temperatures as a result of limited cooling or to piston and ring groove design. Where it is not possible to do anything about the high temperatures or to avoid them by avoiding long climbs at low air speed, light aircraft operators have met with varying degrees of success through use of detergent oils, containing additives to reduce the tendency toward ring sticking. Some such

TABLE VI

Analysis of Typical Exhaust Rocker Box Coke from a Radial Air Cooled Engine

Constituent	*Weight Per Cent Range*	*Typical*
Oil	4 to 30	18
Oxidation Products	0.5 to 3	2
Carbon	11 to 46	41
Volatile Matter	2 to 26	19
Free Mineral Matter	17 to 33	20
		100
Element Analysis		
Lead, Total Wt., %	10 to 20	16

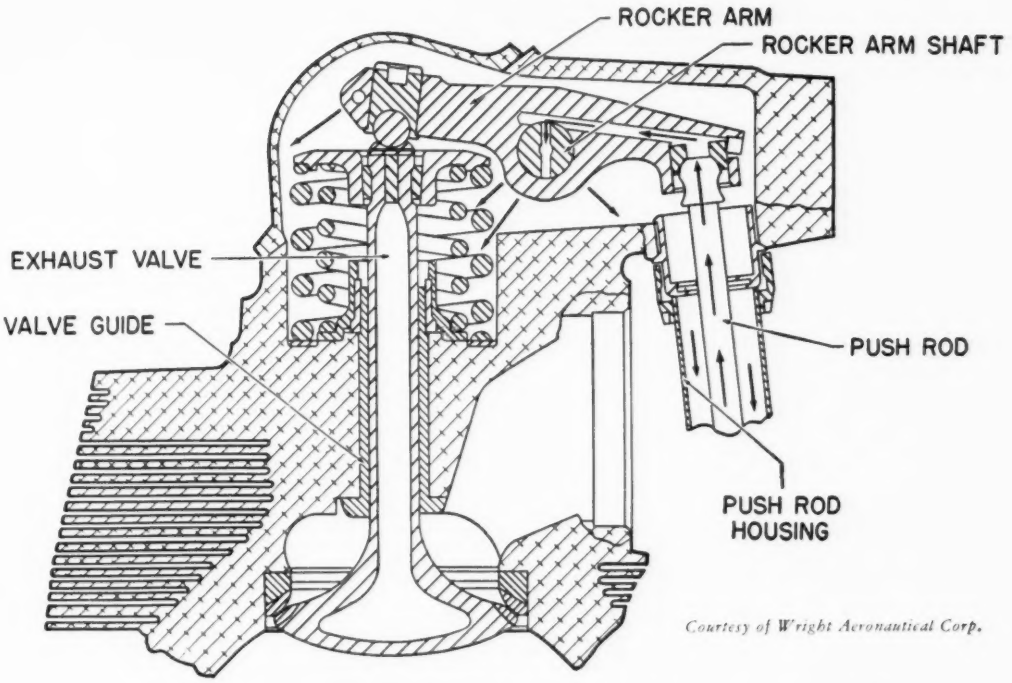


Figure 7 — Section through exhaust valve and port of Wright Cyclone engine Series 18 BD.

oils have other properties making them unsuitable for aircraft however, and engine manufacturers and major oil companies recommend the use of such oils only if the oil is specially developed and thoroughly tested for aviation use, as discussed later.

Service Experience

It should not be inferred from the foregoing discussion of service problems that service experience with present aircraft engine oils is fraught with deposit problems, corrosion, and other ills, for this is not the case. Over-all aircraft engine oil performance at the present time is excellent, having attained record levels in extended time between overhauls and drain periods believed to be wellnigh impossible a few years ago. Thus some engine models are satisfactorily operating 1500 hours between engine overhaul with no scheduled oil drains between overhauls. This is equivalent to approximately 330,000 aircraft miles between overhauls and oil drains. Other models are operated 1200 to 1400 hours in faster aircraft, representing up to 420,000 miles between overhauls. Even the newest post-war engines are being operated 800 to 900 hours between overhauls, figures which were not attained by even the most thoroughly developed engines of ten to fifteen years ago.

All of this achievement, together with the extension of U. S. operated airline routes across both oceans and around the globe, has been accomplished by airlines using the current type of highly refined straight mineral aircraft engine oil. New standards of engine reliability and performance have been set during the post-war era with this oil, at the same time that airline passenger miles were undergoing a three-fold increase and newer and faster aircraft were placed in service.

Although this is a record in which the airline, aircraft and engine manufacturing, and petroleum industries take justifiable pride, there is no complacency or satisfaction with current performance in any quarter. It has truly been said of aviation that research and development are the price of leadership, therefore research in improved engine oils is constantly underway in leading petroleum laboratories.

DEVELOPMENT OF IMPROVED AIRCRAFT ENGINE OILS

The search for improved aircraft engine oils is a long process that begins when the need for improvement is uncovered by oil company aviation service engineers or demonstrated to them by aircraft operators or engine builders. Laboratory groups dealing with manufacturing process, chemical research and additive development go to work to investigate means of obtaining the desired objective, which often must take a new approach previously untried or not yet applied to aviation oils.

The first step in the development program is

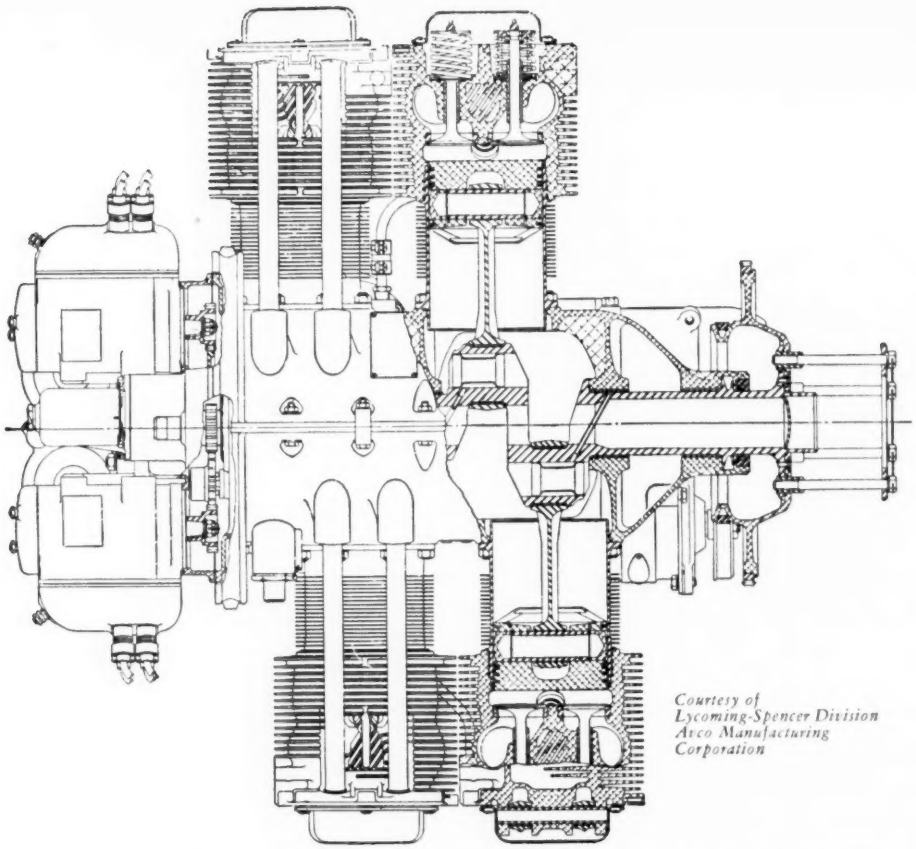


Figure 8 — Longitudinal section of Lycoming Model O-235-C horizontally-opposed 4 cylinder aviation engine.

obtaining supplies of experimental material, whether it be oil made by a new process or compounded with new additives. This is followed by physical and bench testing of samples to make sure specification tests will be met and to provide an indication of performance from small-scale laboratory or "bench" tests of corrosion protection, oxidation stability, deposit-forming properties, high and low temperature stability, storage stability, and other considerations.

Products showing promise in the screening tests are submitted to single-cylinder laboratory engine tests using procedures and equipment designed to evaluate the positive quality features of an improved oil such as engine cleanliness, corrosion protection, valve lubrication, etc., and also to guard against undesirable features that may have been introduced as a result of the change. Experimental oils which successfully pass the small engine tests are thoroughly tested in larger engines, often employing small aircraft engines or single-cylinder aircraft engine test rigs, at operating conditions selected to simulate the full-scale conditions at which performance is to be evaluated. Operating conditions of these units can be varied over the full range of engine in-flight conditions and simulated flight cycles are used. Lubricants can be rated on the basis of piston varnish, piston-ring wear, valve and valve-guide performance and deposits, valve burning, combustion chamber deposits and bearing corrosion — to name only a few of the important qualities.

Oils which still look good after laboratory engine tests should then be tested in full scale multi-cylinder aircraft engines on a test stand. All phases of engine performance, aside from actual flight operation itself, may be evaluated in this manner, using full cycles of flight operation. Conditions are controlled to in-flight values, with the exception that the engine never leaves the ground.

The exceptional or outstanding improved products which reach this point must then pass the final test of flight service use, for there is no substitute for full-scale service evaluation. The aid of progressive airline or aircraft fleet operators is often enlisted at this point, for they stand to gain from improved oils through better engine performance or relieved deposit conditions, as does the oil sup-

plier. With the operator's cooperation, the improved oil is introduced into service where its performance may be directly compared with that of the present oil after operation at like conditions for a full overhaul period in a number of engines. Only in this way can the final evaluation be made—whether the improved oil affords a significant improvement in engine conditions, whether it is merely just as good as present oil, or whether it has actual short comings in full-scale service operation.

From the foregoing it might be concluded that the development of improved oils is an expensive process, and this is so. It may be repeated that the price of leadership is research and development, and the price of research in aviation lubricants is high if only because of the many factors which must be evaluated before an improved product can be safely introduced.

Additive Aircraft Engine Oils

Improvement in the performance of the best available straight-mineral oils is under intensive development through the use of oil additives blended in the oil to enhance specific performance qualities. In certain high-power engines and even in some models of light plane engines, engine deposits have become a major consideration in efforts to improve engine reliability and economy of operation. Improvements in refining technique alone are not sufficient to provide the desired degree of improvement in oxidation resistance and detergent-dispersive characteristics, however, the use of additives offers promise for attaining the desired objectives.

The desirability of using additives in aircraft engine oils and in fact the use of selected additives for specific purposes is not new. Attempts to incorporate oxidation resistant and detergent-type additives in aircraft engine oils date back more than fifteen years, following shortly after the successful application of such additives to lubricants for other types of internal combustion engines. Likewise oiliness additives have been required in the lubricants for some foreign sleeve-valve radial engines for many years, and at one time anti-wear agents were required in the lubricants approved by one of the large manufacturers of engines in the United States.

Early attempts to employ conventional or even specially developed additives of a more-or-less conventional type in aircraft engine oils met with but little success, particularly where such oils were rigorously service tested. Either the expected benefits of the oil failed to show up in severe service, or if the desired degree of oil stability and engine cleanliness was demonstrated, some other feature of engine operation suffered with the additive oil, or operational features rendered the oil unusable. Among the difficulties experienced to greater or lesser degree with additive oils have been spark plug fouling and abnormal combustion chamber and

Figure 9—Pistons from a special aircraft engine oil test in a 4-cylinder opposed aircraft engine, illustrating cleanliness properties of additive-type oils.

Top row shows results with straight mineral aircraft engine oil; ring sticking occurred at 13 hours.

Bottom row of pistons shows performance with additive-type aircraft engine oil; test was arbitrarily terminated after over 100 hours operation. No stuck rings.

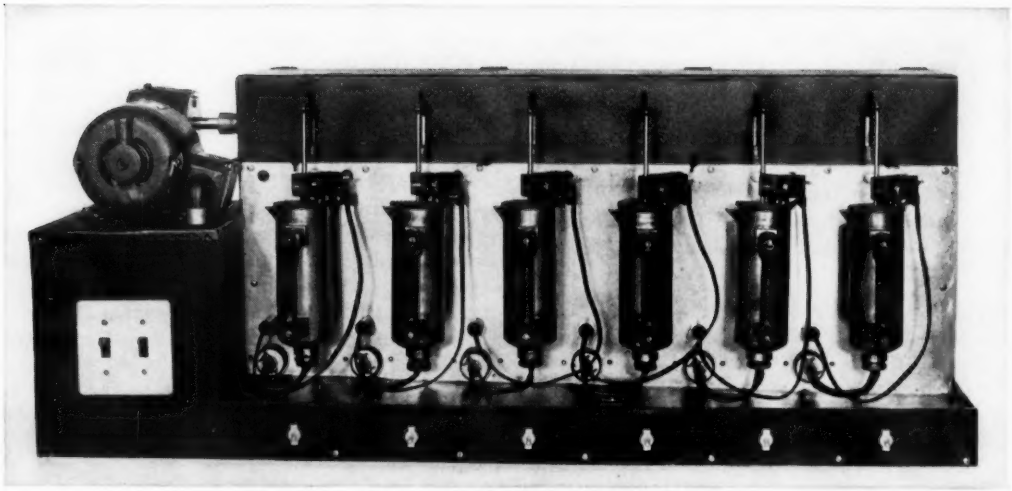


Figure 10—Bench test apparatus for evaluation of valve guide corrosion and deposition properties.

exhaust valve deposits, severe corrosion of bronze exhaust valve guides, effects upon engine bearing metals, and increased tendency toward formation of watery sludges at low temperatures. All of these short-comings were not found in every one of the additive oils tried, however, the net effect was such as to create discouragement that a satisfactory additive oil could be obtained.

Some members of the petroleum industry realized, however, that the answer to further oil improvement depended upon finding or developing entirely new types of additives which would be effective in combatting aircraft engine deposits but have none of the draw-backs previously encountered. Accordingly, long-range research was undertaken to create such products through extensive development programs of the pattern described earlier in this article.

These efforts have culminated recently in the development of a number of additive oils, some of which have been proven airworthy and are now undergoing thorough and painstaking service evaluation in different types of engines and flight operations. The anticipated benefits in reduced engine deposits and improved engine life from highly stable, oxidation resistant, detergent-dispersive oil are of practical value in a dollars-and-cents manner to operators. The military need for such improvement in certain severe types of service is just as great as that of commercial operators. Only thorough-going flight evaluation under the most severe conditions can reveal whether an answer is now at hand or whether petroleum research must seek still further for effective solutions.

Addition of Foreign Materials to Engine Oil

The addition of packaged oil additives, dopes, EP agents or similar materials to aircraft engine oils is considered undesirable since these materials may be unsafe for use in aircraft engines in the absence of any tried and proven background. Highly promoted addition agents generally contain known compounds or combinations of compounds which have been evaluated and rejected for aircraft engine use by petroleum refiners or aviation engineers. Some of these materials may have definite benefit for certain specific properties, but other characteristics make them entirely unsuitable for aviation engines. Since oil refiners incorporate into their products the optimum combination of properties required, based on the best available information and research techniques, it is not good practice to add unknown materials to engine oils.

SUMMARY

Aircraft engine lubrication is both an art and a science, highly developed through years of cooperative endeavor by aircraft engine builders and operators and the petroleum industry. The present high standards of engine and oil performance, mutually interdependent upon one another, are the result of such cooperation. Excellent though the present performance is, beyond even the goals of only a few years past, further improvement is being sought through new and improved oils now being flight service tested. Even so, the dynamic nature of the aircraft industry suggests that today's new oils, if proven adequate for the present problems, may not be the ultimate answer for tomorrow's operations. The petroleum industry is prepared to make still further improvements through its research facilities.

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